Meteoroid Ejecta of Lunar Secondaries Engineering Model

Anthony M. DeStefano

NASA/MSFC/EV44 Natural Environments

Applied Space Environments Conference 2021

Outline

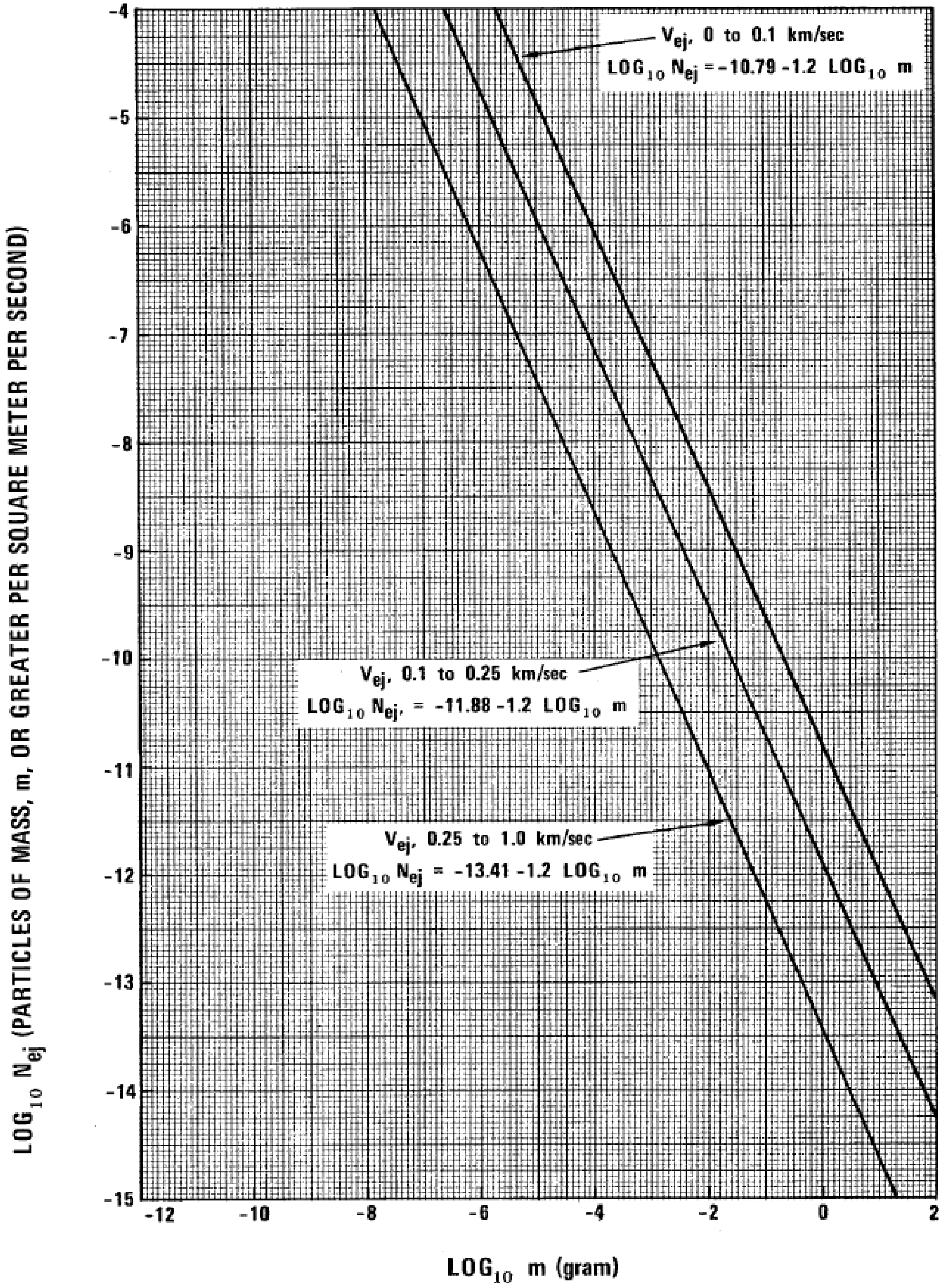
- A Typical Meteoroid Ejecta Model Algorithm
- Current Meteoroid Ejecta Environment – NASA SP-8013
- Updated Model – Meteoroid Ejecta of Lunar Secondaries Engineering Model (MELSEM) – under NESC review
  - Primary Environments
  - Asset Geometry and Location
  - Scaling Laws
  - Secondary Environment at Asset
- Risk Assessment – Probability of No Penetration

Typical Meteoroid Ejecta Model Algorithm

1. **What are the primary impactors?**
   a) Cumulative flux as a function of impactor mass
   b) Impactor density
   c) Possibly angular and location-dependent information
2. **How to convert primary mass flux into ejected mass flux?**
   a) Scaling laws – extrapolations from laboratory experiments and/or theory
3. **How is the ejected mass flux distributed – starting from primary impact location?**
   a) Solid angle
   b) Particle size and density
   c) Speed
4. **For a given observer, what is the total ejected mass flux, accounting for impacts over the entire surface of the Moon?**
   a) Solid angle
   b) Particle size and density
   c) Speed

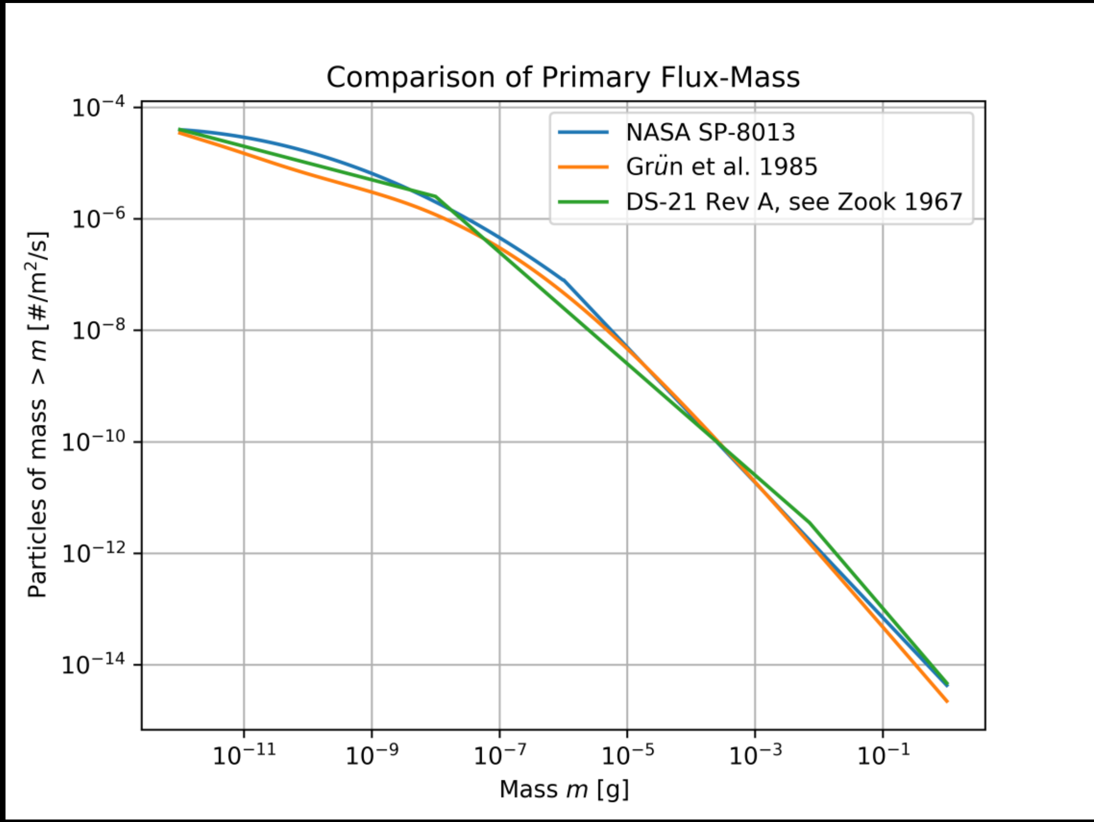
NASA SP-8013 – Lunar Ejecta Environment

- The Cross-Program Design Specification for Natural Environments (DSNE) rev. H, Section 3.4.8.2 points to NASA SP-8013, Section 3.2 for the **Meteoroid Ejecta Environment**
  - **Power-law expressions are given for various ejecta speed ranges of the cumulative flux as a function of ejecta particle mass**
  - **A single particle density is assumed at 2.5 g/cm^3**

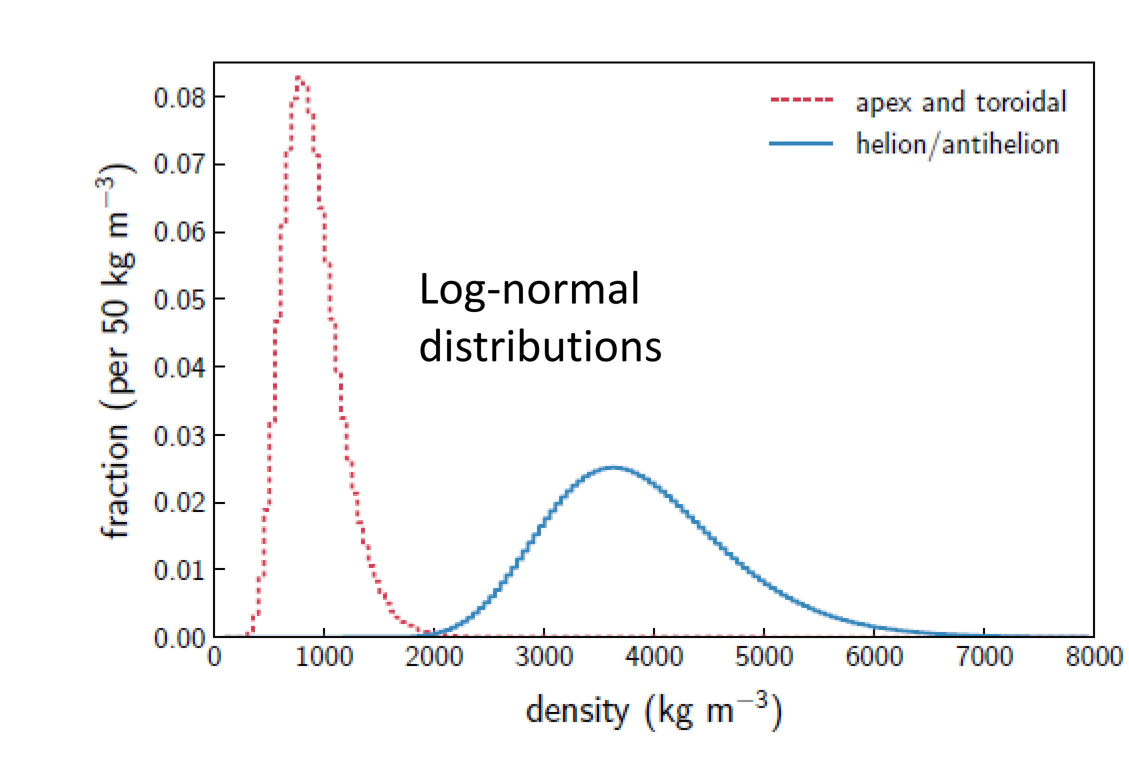


NASA SP-8013 – Lunar Ejecta Environment

- NASA SP-8013 is consistent with Grun et al. 1985
    - Grun et al. 1985 is used to scale the Meteoroid Engineering Model (MEM) for primary sizes of 1 ug to 10 g
- Scaling laws implied in NASA SP-8013 are from Zook 1967



Sporadic meteoroid flux (low and high density populations in MEM)



Moorhead 2019

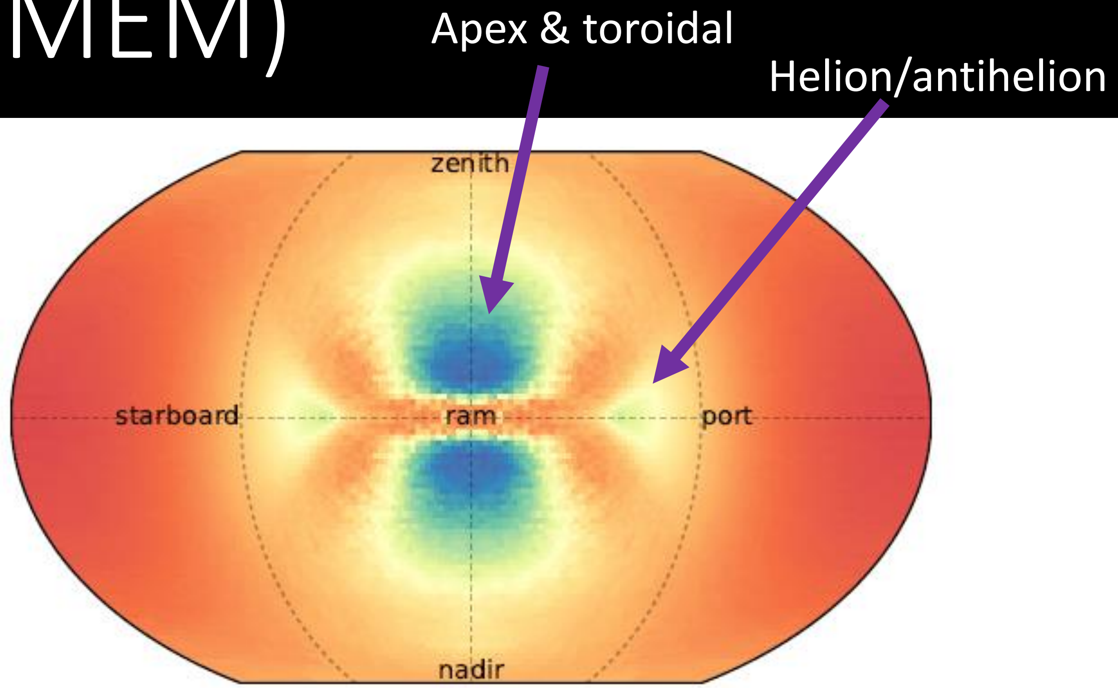


Figure 2.4: Average interplanetary meteoroid speed as calculated by MEM 3 for a spacecraft that is orbiting the Sun at 1 au but is not near the Earth. Color indicates the average speed of all meteoroids originating from a particular direction. The directionality is plotted in a body-fixed frame, in which the center (0° in azimuth and 0° in altitude) corresponds to the spacecraft's direction of motion.

Lunar Surface Ephemeris for MEM – JPL Horizons

- A total of 148 ephemeris files generated for a fixed location on the Moon
  - 19-year (Metonic cycle) time period of trajectory
  - 5-degree latitude intervals from south pole to north pole
  - 90-degree longitude intervals
  - Timestep ~ 16 hours 40 minutes (10,000 total)

```
From:   Horizons Ephemeris System <horizons@ssd.jpl.nasa.gov>
Sent:   Wednesday, March 4, 2020 9:58 AM
Subject:        [Horizons] MAJOR BODY #C(usr={0.,0.,.600^G}@301)_T(301) (1/1)

 Automated mail xmit by MAIL_REQUEST, PID= 3449 Wed Mar  4 07:58:11 2020
++++++++++++++++++++++++++++++++ (part 1 of 1)  ++++++++++++++++++++++++++++++++
*******************************************************************************
 Revised: July 31, 2013             Moon / (Earth)                         301

 GEOPHYSICAL DATA (updated 2018-Aug-15):
  Vol. mean radius, km   = 1737.53+-0.03    Mass, x10^22 kg        =    7.349
  Radius (gravity), km   = 1738.0           Surface emissivity     =    0.92
  Radius (IAU), km       = 1737.4           GM, km^3/s^2           = 4902.800066
  Density, g/cm^3        =    3.3437        GM 1-sigma, km^3/s^2   =  +-0.0001
  V(1,0)                 =   +0.21          Surface accel., m/s^2 =    1.62
  Earth/Moon mass ratio = 81.3005690769     Farside crust. thick. = ~80 - 90 km
  Mean crustal density   = 2.97+-.07 g/cm^3 Nearside crust. thick.= 58+-8 km
  Heat flow, Apollo 15   = 3.1+-.6 mW/m^2   Mean angular diameter = 31'05.2"
  Heat flow, Apollo 17   = 2.2+-.5 mW/m^2   Sid. rot. rate, rad/s = 0.0000026617
  Geometric Albedo       = 0.12             Mean solar day         = 29.5306 d
  Obliquity to orbit     = 6.67 deg         Orbit period           = 27.321582 d
  Semi-major axis, a     = 384400 km        Eccentricity           = 0.05490
  Mean motion, rad/s     = 2.6616995x10^-6  Inclination            = 5.145 deg
  Apsidal period         = 3231.50 d        Nodal period           = 6798.38 d
                                   Perihelion  Aphelion    Mean
  Solar Constant (W/m^2)           1414+-7     1323+-7     1368+-7
  Maximum Planetary IR (W/m^2)     1314        1226        1268
  Minimum Planetary IR (W/m^2)        5.2         5.2         5.2
*******************************************************************************
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*******************************************************************************
Ephemeris / MAIL_REQUEST Wed Mar  4 07:58:10 2020 Pasadena, USA  / Horizons
*******************************************************************************
Target body name: Moon (301)                      {source: DE431mx}
Center body name: Moon (301)                      {source: DE431mx}
Center-site name: (user defined site below)
*******************************************************************************
Start time      : A.D. 2020-Jan-01 00:00:00.0000 TDB
Stop  time      : A.D. 2039-Jan-01 00:00:00.0000 TDB
Step-size       : 10000 steps
*******************************************************************************
Center geodetic : 0.00000000,0.00000000,0.6000000 {E-lon(deg),Lat(deg),Alt(km)}
Center cylindric: 0.00000000,1738.00000,0.0000000 {E-lon(deg),Dxy(km),Dz(km)}
Center pole/equ : IAU_MOON                        {East-longitude positive}
Center radii    : 1737.4 x 1737.4 x 1737.4 km     {Equator, meridian, pole}
Output units    : KM-S
Output type     : GEOMETRIC cartesian states
Output format   : 3 (position, velocity, LT, range, range-rate)
Reference frame : ICRF/J2000.0
Coordinate systm: Ecliptic and Mean Equinox of Reference Epoch
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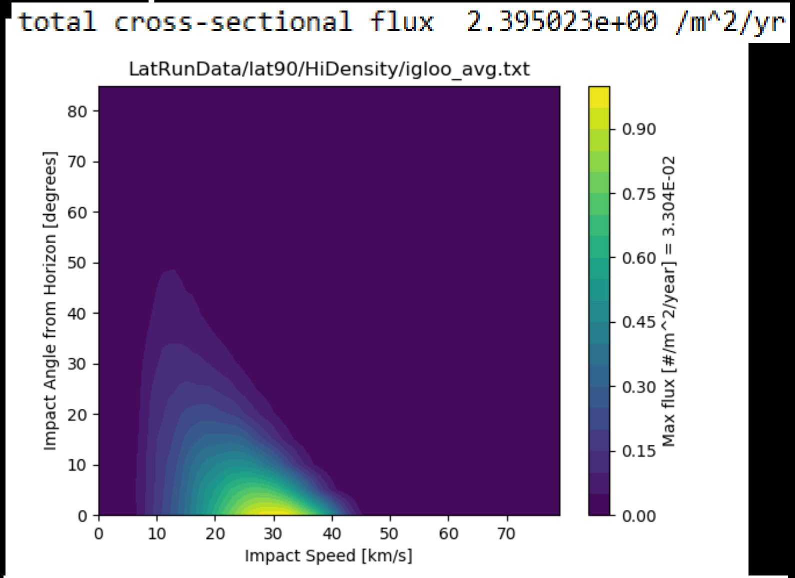
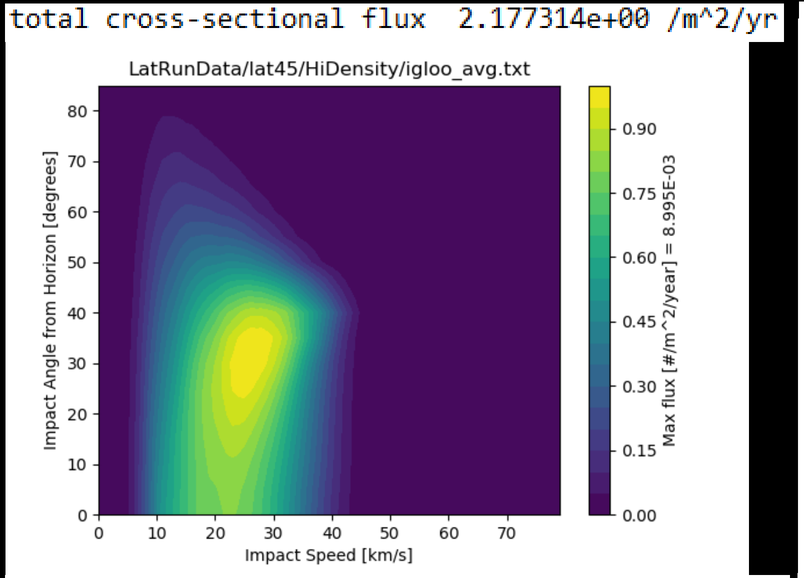
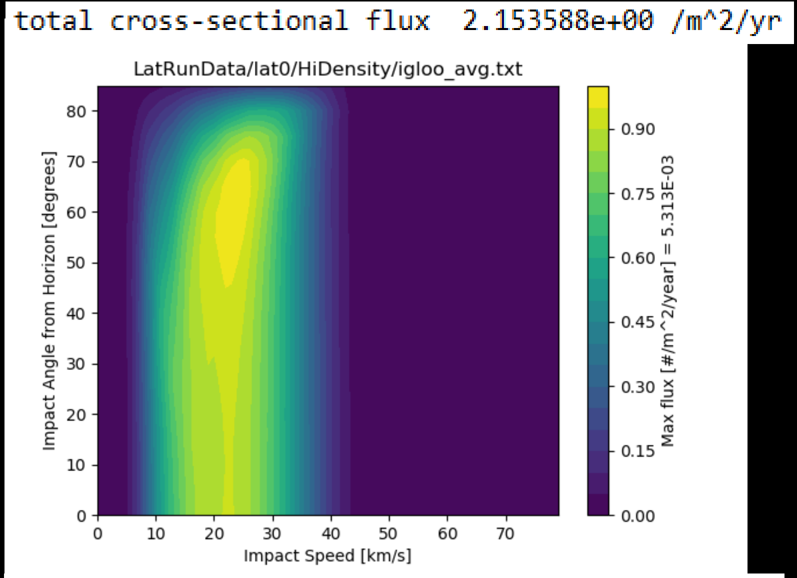
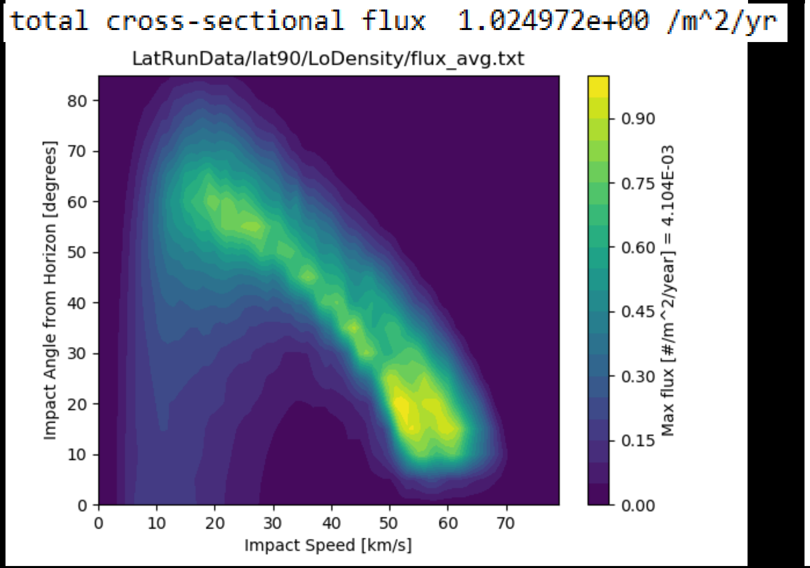
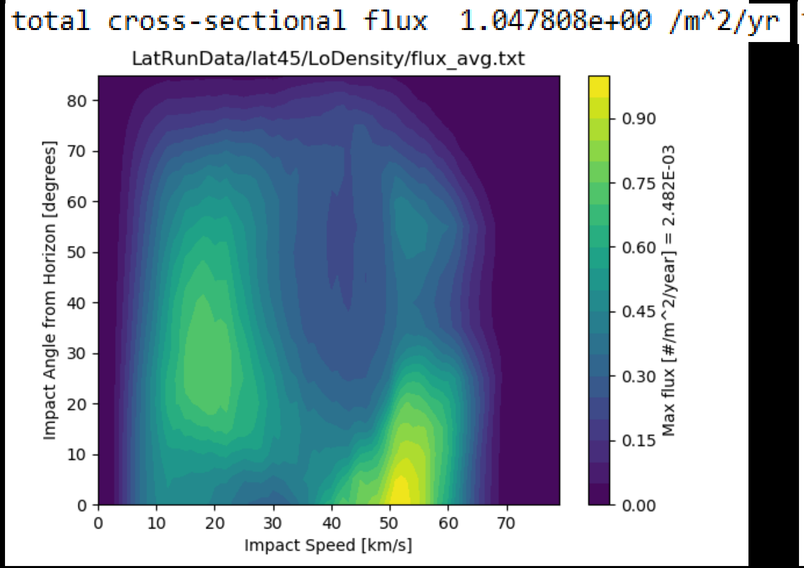
Sporadic meteoroid flux (angle/speed) and latitudinal dependence on the lunar surface

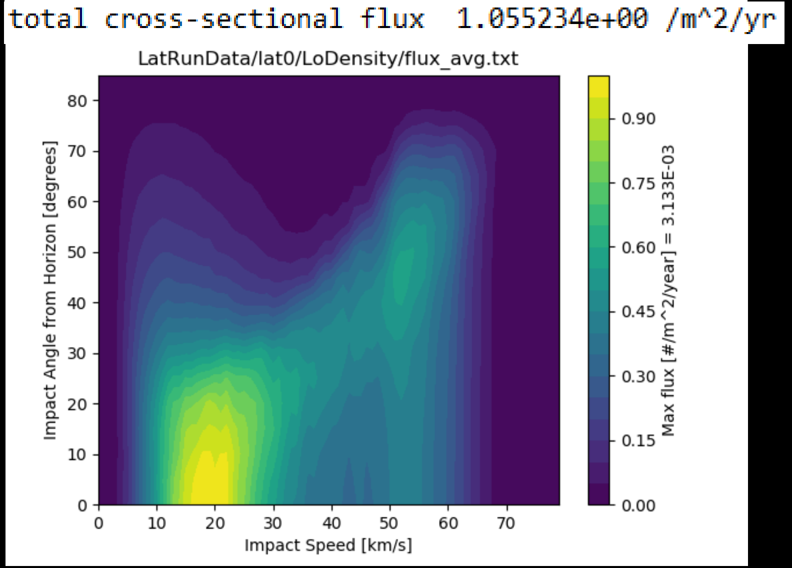




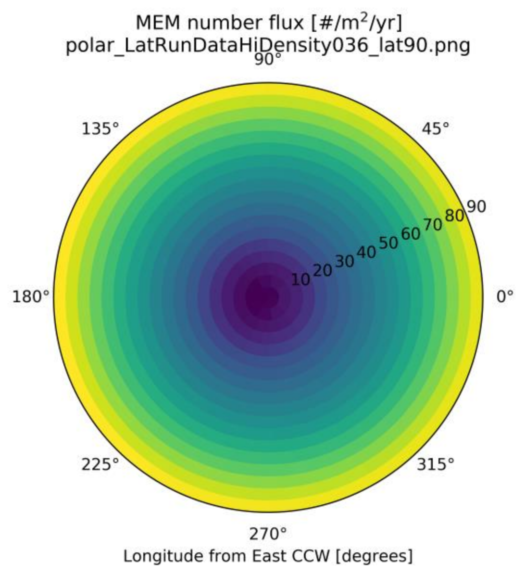


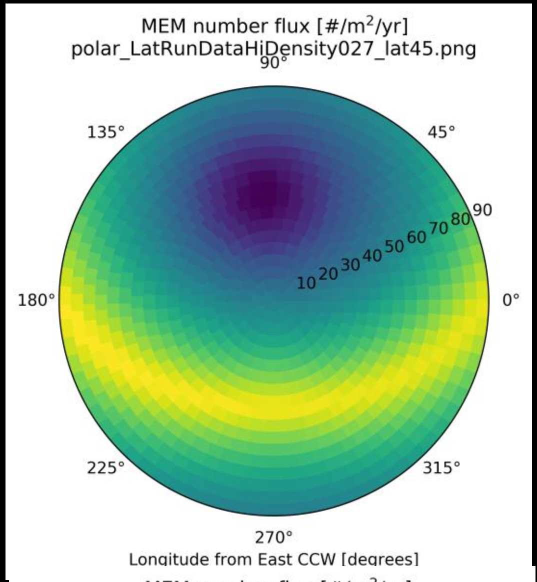


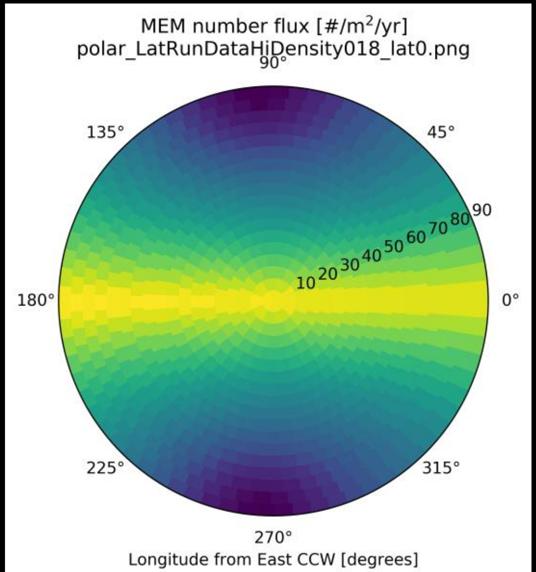


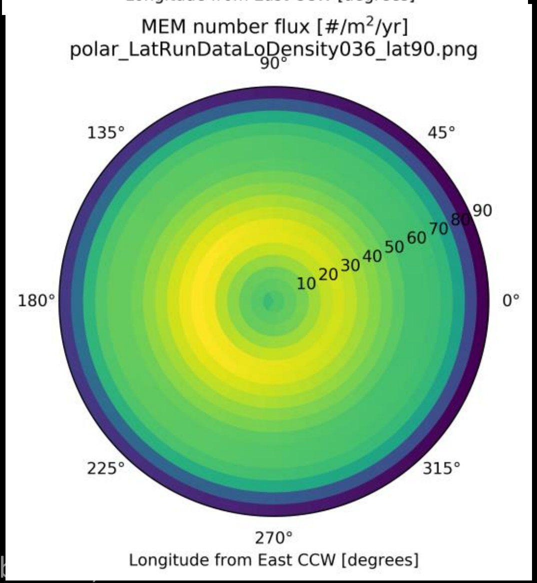


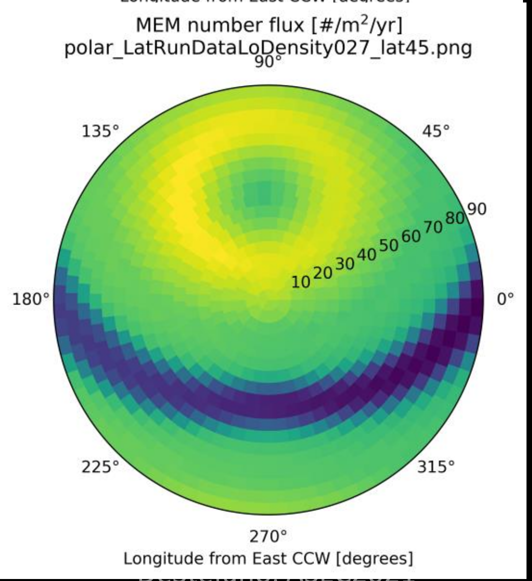
Sporadic meteoroid flux (alt/az) and latitudinal dependence on the lunar surface

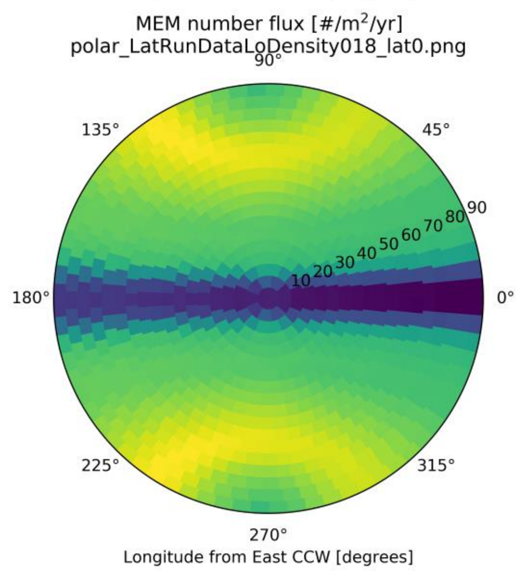






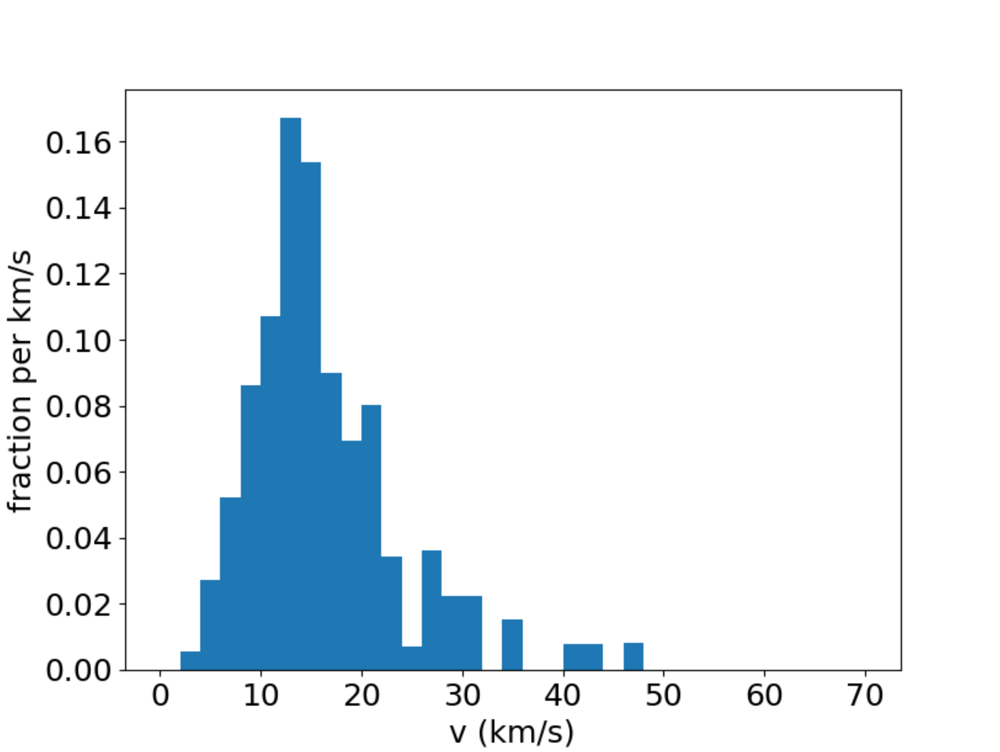






Near Earth Object (NEO) flux (Brown et al. 2002) at the lunar surface

$$g_{☾}(m) = 2.89 \times 10^{-11}\,\mathrm{m}^{-2}\,\mathrm{yr}^{-1} \cdot m^{-0.9}$$



- Moorhead (see memo OSMA/MEO/Lunar-001) computed the NEO flux at the lunar surface based on Brown et al. 2002 and velocity distribution of bolides reported by the Center for Near Earth Object Studies (CNEOS)
- In MELSEM, we approximate the angular distribution of fluxes at the lunar surface by the low-density population of MEM

Asset Geometry and Location

- The **asset**, or observer, is the physical object at which the meteoroid ejecta is collected from all impacts over the entire surface of the Moon to generate the meteoroid ejecta environment
  - Typical simplifying shapes of the object include:
    - Sphere
    - Cylinder
    - Rectangular Prism
  - The asset can be made of any number of these shapes, but for simplicity, a cylinder is often chosen for a lunar lander
  - The location of the asset can be on the lunar surface or any distance above the lunar surface
    - In general, a full trajectory could be used, but a single-point location is used for simplicity

Impact-ejecta scaling model (Housen & Holsapple 2011)

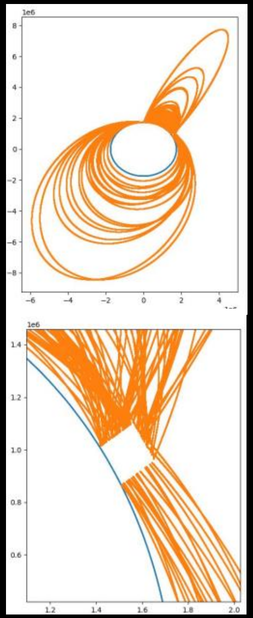
- $\frac{M}{m} = \frac{3k}{4\pi}\frac{\rho}{\delta}\left[\left(\frac{x}{a}\right)^3 - n_1^3\right]$
- $\frac{v}{U} = C_1\left[\frac{x}{a}\left(\frac{\rho}{\delta}\right)^{\nu}\right]^{-\frac{1}{\mu}}\left(1 - \frac{x}{n_2 R}\right)^p$
- Where $n_1 a \leq x \leq n_2 R$

- x acts parametrically for the ejecta mass M greater than v function, and the ejecta speed v function
- R is the crater radius, dependent on the impact and target parameters
- a is the impactor radius

*Assuming isotropic ejecta with a speed distribution $f(v) \sim v^{-\alpha}, \alpha = 2.2$

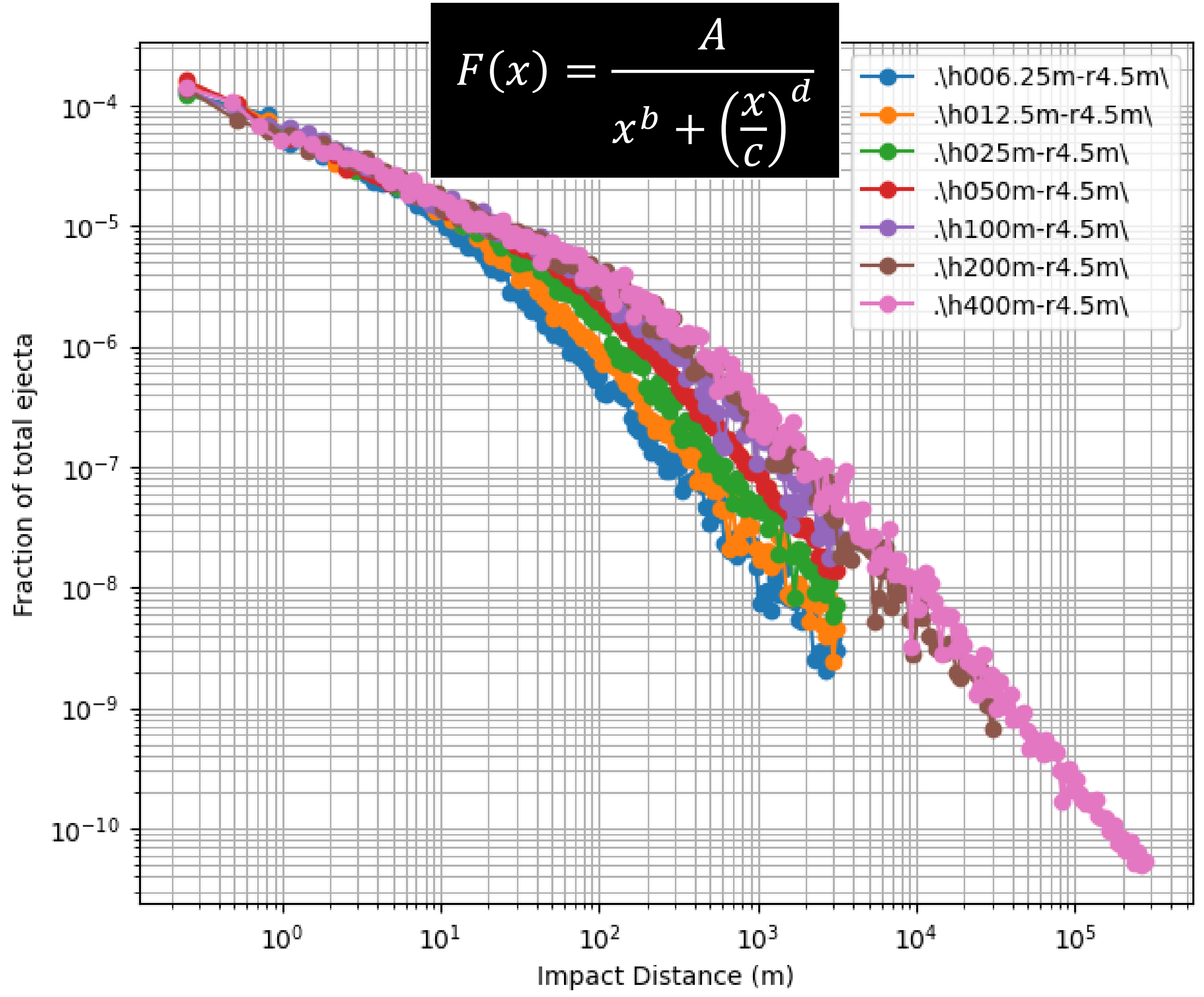
Differential ejecta flux vs. distance

- Various cylindrical lander heights were simulated using Monte Carlo for various impact distances
  - For simplicity, these simulations used 2D due to the symmetry – off radial hits assumed to have same width as radial width (conservative)
- Orbits solved using RKF45 integration of equations of motion (variable time stepping):
  - $\dot{r} = v$
  - $\dot{v} = a$
  - $a = \frac{F}{m} = -\frac{g}{r^2}\ \hat{r}$
- MC sims show:
  - $b \sim 0.52$ and $d \sim 1.64$, very close to the analytic estimates!



A	b	c	d
6.590499808281237285e-05	4.799954260154283281e-01	4.970231009182878523e+00	1.582324570148092135e+00
6.725788561606771410e-05	5.133359708764714258e-01	7.542870647049745969e+00	1.625263077649770294e+00
6.053712106917220458e-05	4.914658055311414420e-01	1.164578504479363907e+01	1.618243493791829524e+00
6.070406655613365822e-05	5.422614424214287077e-01	1.994394238437383748e+01	1.671689450913666608e+00
6.212440689731742486e-05	5.513102507161407040e-01	2.961635841293069404e+01	1.679567153701406967e+00
5.641655647329060720e-05	5.190308920930193359e-01	4.032083050879096220e+01	1.657231149863489295e+00
5.810427002251947198e-05	5.352810437152915046e-01	4.555514017833936435e+01	1.617576125182017766e+00

$$F(x) = \frac{A}{x^b + \left(\frac{x}{c}\right)^d}$$

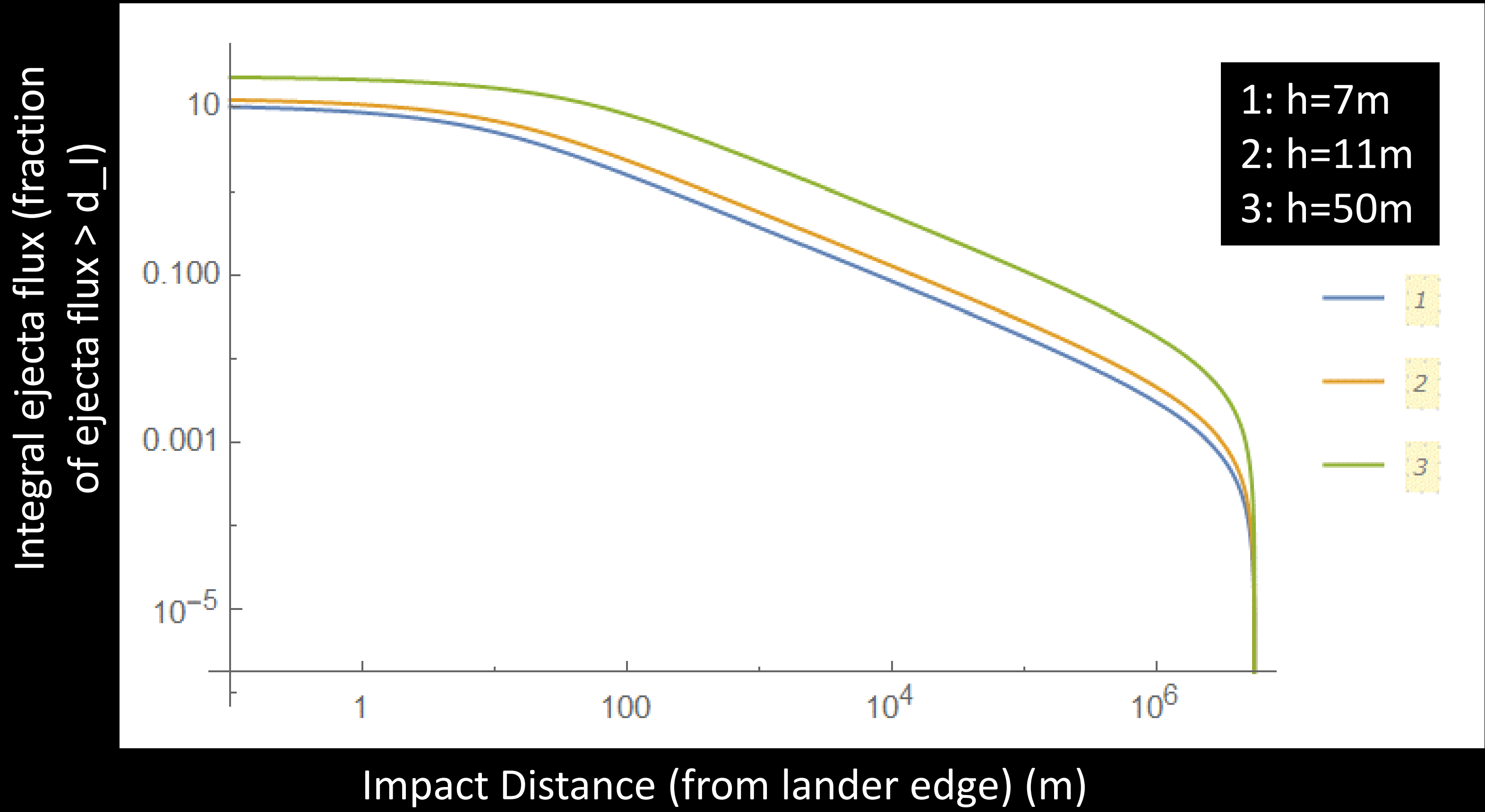


The c parameter is related to the distance scale ($x = c^{\frac{d}{d-b}} \approx c^{1.463}$) at which the height of the lander is not driving the ejecta flux

Integral ejecta flux vs. Impact distance

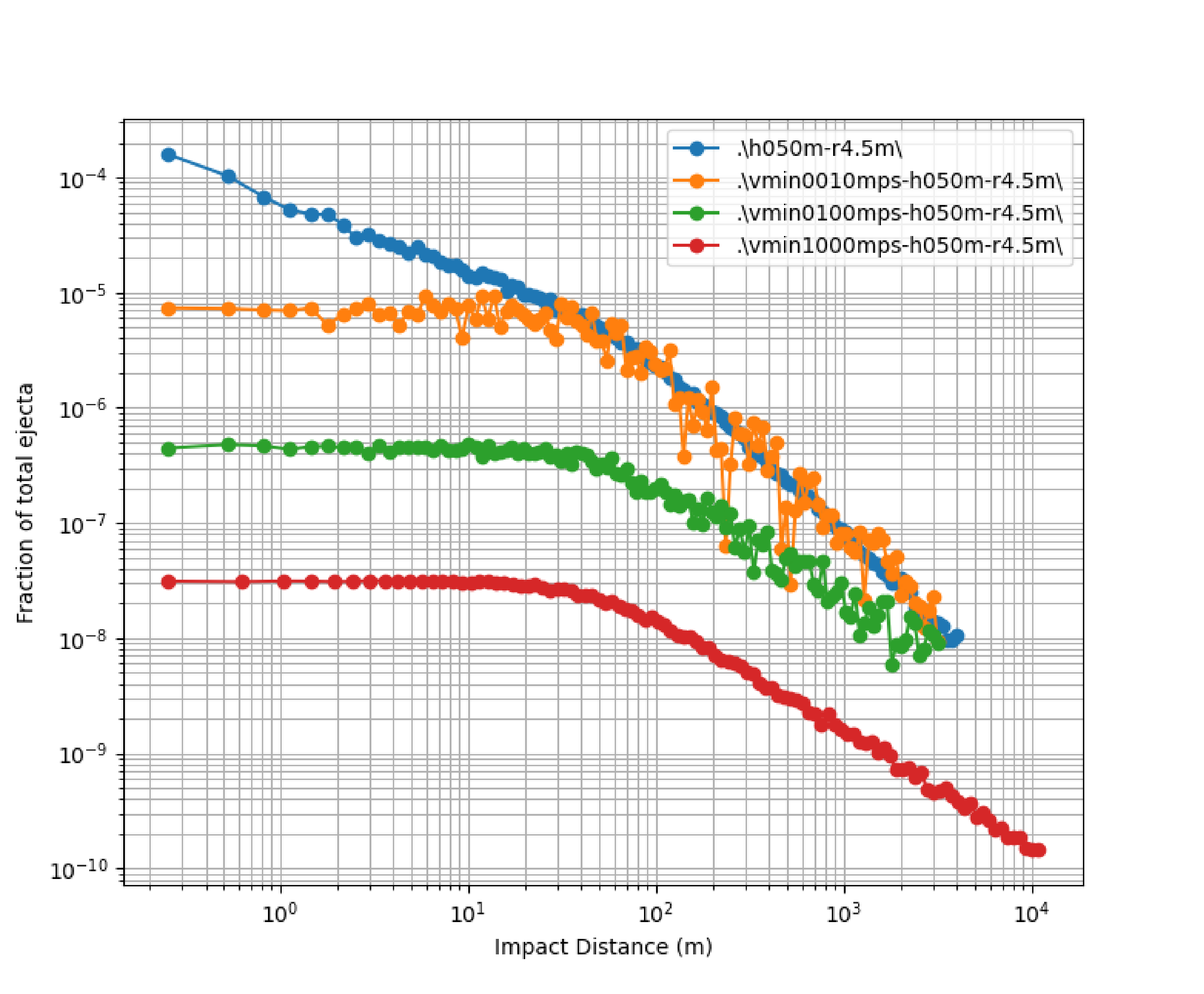
- $I_{ejecta\ flux}(d_I) = \int_{d_I}^{\pi R_m} dx\, F(x)$, the integral ejecta flux as a function of impact distance d_I
- $F(x) = \frac{A}{x^b + \left(\frac{x}{c}\right)^d}$, the differential ejecta flux as a function of distance x

- From analytic results, we expect:
  - $b = \frac{\alpha - 1}{2} = 0.6$ (0.52 from MC), and
  - $\mathrm{d} = \frac{\alpha + 1}{2} = 1.6$ (1.64 from MC)
  - Due to the speed distribution $f(v) \sim v^{-\alpha}, \alpha = 2.2$



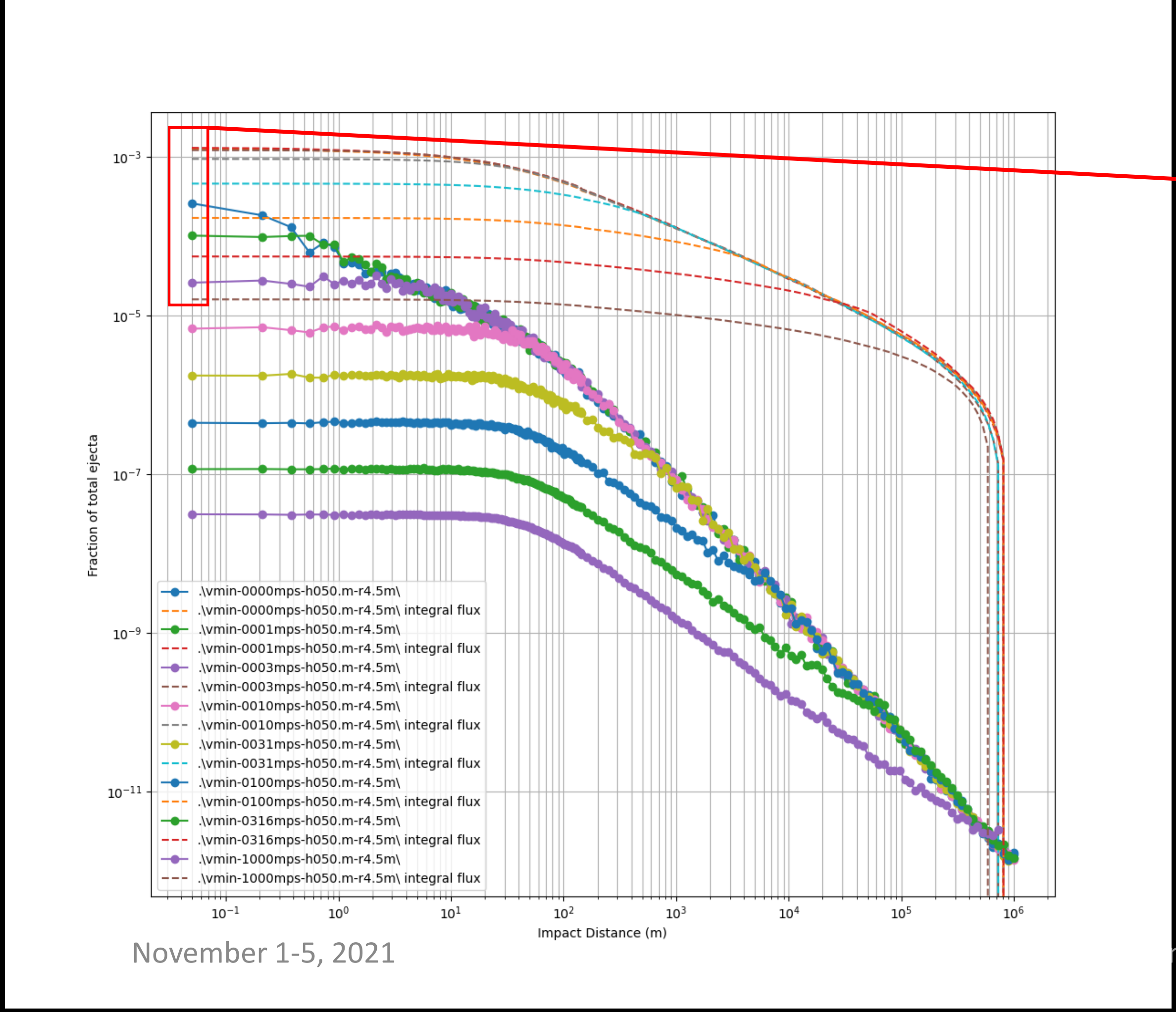
Effects of minimum ejecta speed on differential ejecta flux

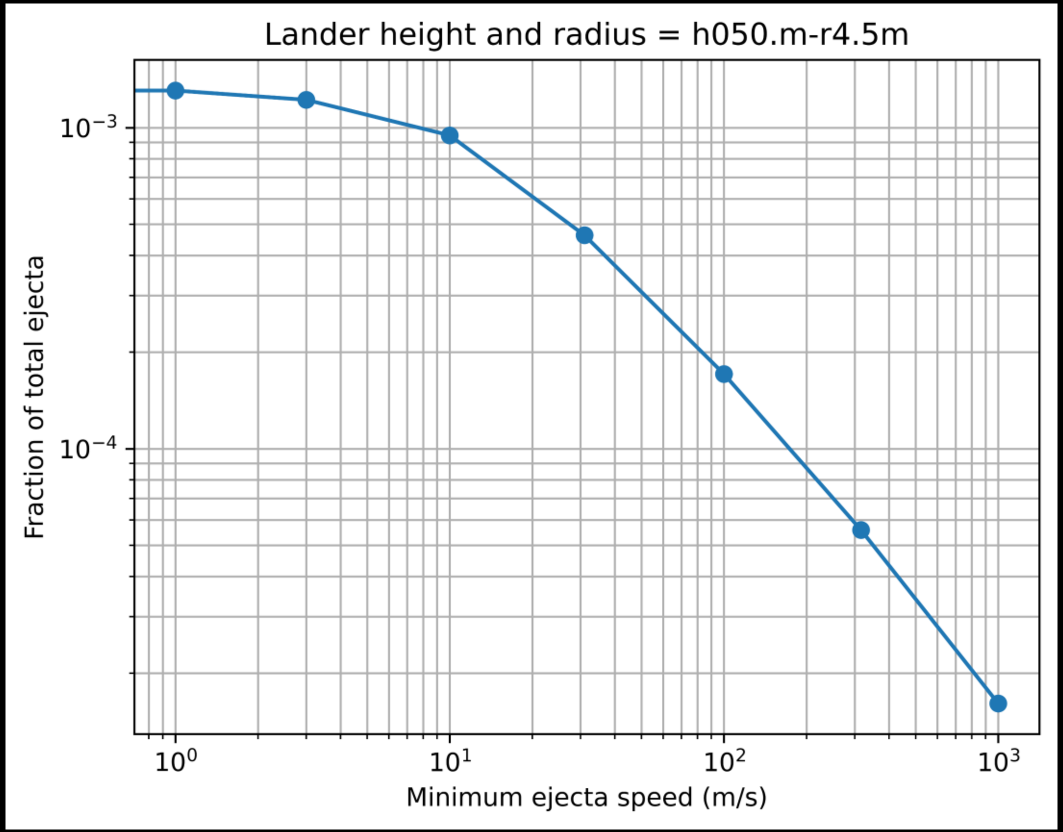
- Imposing a minimum ejecta speed eliminates the bulk of the ejecta at close distances
    - Low-energy ejecta (speed and mass) may be irrelevant to the impact risk
- Further distances are not affected by a minimum speed cut-off
    - Not enough speed to reach far distances in the first place



Differential flux (solid-marked) and integral flux (dashed) vs. min speed cut-off

- Integral flux is flux of ejecta from distances *d* and further, for all speeds greater than *vmin*
- E.g., 86.5% of the ejecta hitting the lander is < 100 m/s





*Assuming isotropic ejecta with a speed distribution $f(v) \sim v^{-\alpha}, \alpha = 2.2$

Probability of No Penetration – Ballistic Limit Equations

- Example of a ballistic limit equation (BLE):
  - For a given particle speed, failure/PNP is defined as the particle diameter above the curve
  - Different shielding designs will achieve different BLEs
- Lunar escape speed is 2.38 km/s
  - Typical M/OD shielding designs might not be as effective for slower meteoroid ejecta
  - If an impact occurs very close to the asset (lunar lander), a small fraction of the ejecta will have speeds greater than lunar escape speed

PERGAMON International Journal of Impact Engineering 26 (2001) 93–104
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www.elsevier.com/locate/ijimpeng

BALLISTIC LIMIT EQUATIONS FOR SPACECRAFT SHIELDING

ERIC L. CHRISTIANSEN* and JUSTIN H. KERR*

*NASA Johnson Space Center, Mail Code SN3, Houston, TX 77058

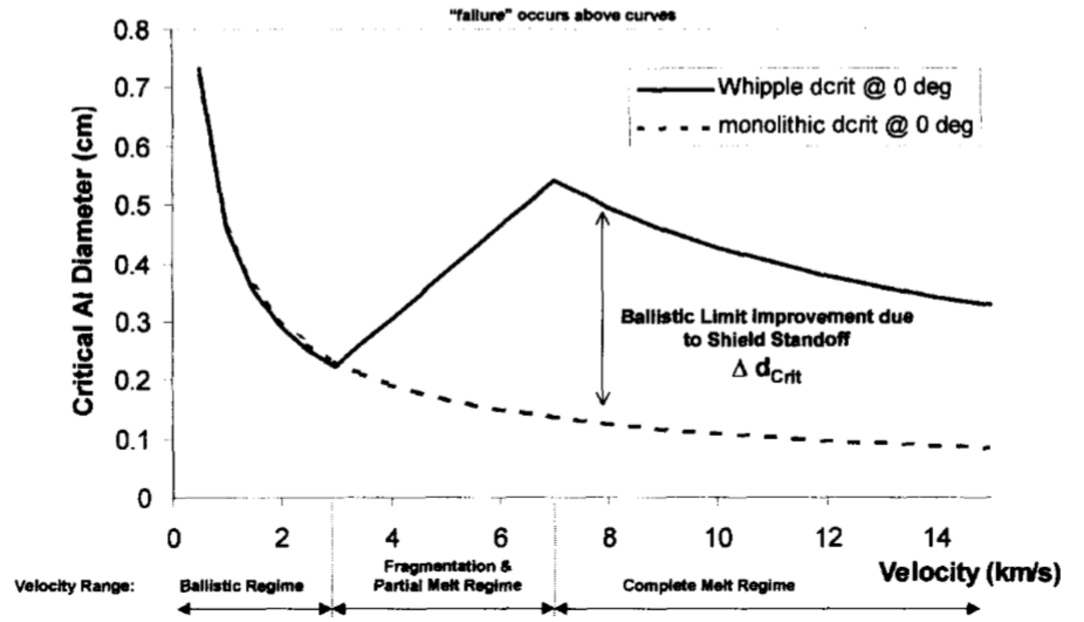

Fig. 4. Illustration of Ballistic Limits for Monolithic and Whipple Shield (equal mass). Failure criterion is shield threshold perforation or detached spall from rear wall. Monolithic is 0.44cm thick Al 6061T6. Whipple is 0.12cm thick Al 6061T6 bumper followed at 10cm by 0.32cm Al 6061T6 rear wall.